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(54) **Title:** AN ELECTROMECHANICAL SWITCH AND METHOD OF FABRICATION

(57) **Abstract:** A micro-electro-mechanical (MEM) switch formed on a substrate allows switching of various types of electrical conductor structures, depending on the desired frequency range of switch transmission and isolation. The switch contains a tilting cantilever arm, which tilts around central points of attachment. At least two conducting electrodes on the cantilever arm and the substrate form at least two air gap capacitors, which when electrically charged provide electrostatic attraction forces that cause the cantilever arm to deflect and tilt until conducting electrodes near the tips of the cantilever arm make electrical contact with fixed electrodes on the underlying substrate. The air gap capacitors on either side of the cantilever points of attachment allow the switch to be driven into both ON and OFF states, thereby eliminating dependence on cantilever mechanical restoring forces One or more holes in the cantilever arm near the air gap capacitors allow air within the gap to escape, thereby reducing the squeeze film damping and increasing the mechanical bandwidth of the switch. Low-temperature, IC compatible processing allows the switch structure to be fabricated directly on substrates containing pre-processed circuits, such as monolithic microwave integrated circuits (MMICs), and on low-cost substrates, such as low temperature co-fired ceramic (LTCC), for the realization of low-cost vertical integration of complex switching circuits, such as RF phase shifter networks.

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AN ELECTROMECHANICAL SWITCH AND METHOD OF FABRICATION

FIELD OF THE INVENTION

The present invention relates to micro-electro-mechanical-systems (MEMS), and, in particular, to a micro-electro-mechanical switch that has high mechanical bandwidth and a transmission bandwidth from DC to more than 30GHz.

BACKGROUND OF THE INVENTION

The use of mechanical switches in electrical networks instead of semiconductor-based switches is particularly desirable in RF systems. This is mainly due to the high insertion losses, at high frequencies, and relatively low isolation of present day semiconductor switches. Moreover, as the operation frequencies of interest in the RF industry continue to increase, these problems become more apparent.

Mechanical switches made by micro machining (MEMS) provide an attractive alternative to semiconductor switches, since they can be built directly on substrates already containing other, active components, such as amplifiers, filters, comparators, or digital circuits. The potential benefits of MEMS switches are lower insertion losses and better electrical isolation, also referred to as dynamic range, between ON and OFF states. The major issues in micro fabricated switches, apart from realizing a fabrication process, are the voltage required to activate the switch and the mechanical bandwidth of the switch structure, which limits how fast the switch can change state. Furthermore, it is important to design the conducting surfaces in the switch to provide the lowest possible

ON resistance. Several MEMS based, electrostatically actuated, switches for RF applications have been disclosed in the prior art.

A first switch design 20 shown in Figure 1 relies on a mechanical restoring force within the switch structure to provide the transition from the ON state to the OFF state, or vice versa, when the externally imposed actuation force is removed. A transmission line 21 and an actuator counter electrode 23 are formed on a substrate 22. A movable structure 24 (*e.g.,* a cantilever) is attached to substrate 22 by a spacer 25. Deposited on cantilever 24 is a second actuator electrode 26 and a switch contact layer 27. Transmission line 21 has a gap under cantilever 24 and switch contact layer 27. When a DC voltage is applied between actuator electrodes 23 and 26, cantilever 24 is pulled towards substrate 22 by an electrostatic attraction force until switch contact layer 27 makes mechanical contact with transmission line 21, thereby closing the gap in transmission line 21. When the actuation voltage is removed, the restoring force of cantilever 24 pulls switch contact layer 27 up, thereby opening switch 20.

An inherent problem with the design shown in Figure 1 is that the mechanical restoring force of cantilever 24 is directly related to its mechanical stiffness, as is the mechanical resonance frequency. Therefore, to achieve high mechanical bandwidth (low switch transition time), it is necessary to have a high mechanical restoring force. Since the actuation force must overcome the mechanical restoring force to switch to the ON state, the requirement for high mechanical bandwidth leads to higher actuation forces, which tends to make switch 20 difficult to use in low-power, low-voltage portable systems, such as mobile telecommunications. The problem is further enhanced by the desire for a high dynamic range between ON and OFF states, which means the gap

between electrodes 21 and 27 in the OFF state must be large enough to minimize capacitive coupling. Larger air gaps between electrodes 23 and 26 in switch 20 will also lead to higher activation voltages, since electrostatic attraction forces are inversely proportional to the second order of the electrode distance.

An alternative switch design 30 shown in Figure 2 provides an external actuation force for both state transitions, leading to lower actuation voltages and better mechanical bandwidth. Switch 30 includes a conductive cantilever 31 attached to a substrate 32 at a central point of suspension 33, about which cantilever 31 can tilt. Two actuator counter electrodes 34 and 35 on substrate 32 are used to generate an electrostatic attraction force to tilt cantilever 31. The tips of cantilever 31 are covered with a high conductivity contact material 36, which makes mechanical contact either with transmission lines 37 or 38 located on substrate 32. In operation, a DC voltage is applied between conductive cantilever 31 and either counter electrode 34 or 35. The resulting electrostatic attraction force causes cantilever 31 to tilt until it makes mechanical contact at one of its tips with either transmission line 37 or 38, thereby forming an electrical connection from the central transmission line 39 to the contacted transmission line 37 or 38. To toggle switch 30, the DC voltage is moved from one counter electrode to the other, causing cantilever 31 to tilt in the opposite direction and make contact with the opposite transmission line. One drawback of the alternative design of Figure 2 is that the entire movable structure in switch 30 must carry the RF transmission signal to be switched. Consequently, the movable structure must be made from a high quality conductive material, such as gold, silver, or copper, to minimize losses. Even so, there are still losses and signal mode dispersion associated with switch 30, since it does not maintain an ideal transmission line

structure. Another drawback is that the movable structure in switch 30 may have long term stability problems, since most highly conductive metals suffer from inferior fatigue properties compared to most dielelectric materials. In addition, the DC switch control signal must overlay the RF signal, thereby requiring additional isolation in the signal path.

An alternative prior art shunt type switch (not shown) does not necessarily require the movable structure to be made of high conductivity material, since the shunt shorts out the RF transmission line to terminate signal propagation. Furthermore, the movable part in the shunt switch is completely free and therefore not subject to the same fatigue problems mentioned above. A potential problem with this shunt switch structure is stiction of the movable structure, which may cause long term failure in the switch.

A further alternative prior art switch structure 40 shown in Figure 3 is yet another tilting cantilever design in which a cantilever 41, constructed from gold with a thin silicon nitride insulation layer 42, is mounted on a substrate 50. Cantilever 41 is free to tilt around a point of suspension 47. In this design, the entire cantilever 41 does not carry the RF signal. Only the tip of cantilever 41, which is coated on the underside with a conductive material 43 makes contact with a transmission line 44. The purpose of a counter electrode 45 is to pull cantilever 41 so as to close switch 40, whereas another counter electrode 46 opens switch 40 and serves to pull the tip of cantilever 41 further away from transmission line 44 to minimize capacitive coupling. Silicon nitride layer 42 prevents a short circuit in the electrostatic actuators when switch 40 is in the ON or OFF state, and also serves to isolate conductive material 43 from the conductive part 48 of cantilever 41, whereby the DC control does not have to overlay the RF signal.

Unfortunately, the switch structure of switch 40 is also subject to concerns about fatigue and long term stability, since the majority of cantilever 41, including the torsional suspension, is made of gold. In addition, the silicon nitride layer 42, which is used as insulator between the conducting part 48 of cantilever 41 and electrodes 45 and 46, is known to suffer from surface charging. Such surface charging can diminish the effective electrostatic force leading to an increase in the required voltage to transition switch 40.

The mechanical restoring force in the movable structure within a switch, such as that shown in Figure 1, is a limiting factor on the external force necessary to actuate the switch, as well as the mechanical bandwidth of the switch structure. If the mechanical restoring force is used to provide state transition in the switch, it must be high enough to allow sufficient mechanical bandwidth. Thus, the movable structure must be rigid, which, in turn, requires the external actuation force used to drive the other state transition to also be high. The present invention avoids this problem through a centrally supported tilting cantilever that is electrostatically actuated in both ON and OFF states. The electrostatic force then becomes a limiting factor in the mechanical bandwidth of the switch; and since the mechanical restoring force of the cantilever is minimized, the required external actuation force will be low. This combination yields microsecond switching times at actuation voltages as low as 5 Volts. The present invention also provides better dynamic range between ON and OFF states, since in the OFF state the structure is deflected beyond its natural point of equilibrium. A further important benefit realized by the present invention is that, by preventing mechanical contact in the electrostatic actuator areas, and by selecting a proper combination of materials for the cantilever, which does not have a solid dielectric between electrostatic actuator

electrodes, problems with surface charging, diminished actuation forces and stiction can be eliminated.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a MEMS switch structure that may be inserted in RF transmission line structures with minimal loss due to signal reflection and mode dispersion.

It is another object of the present invention to provide a MEMS switch structure with a higher mechanical bandwidth and a lower switch activation voltage than that required by prior art switches.

It is a further object of the present invention to provide a MEMS switch structure which has a better dynamic range between ON and OFF states than prior art switches and which has improved reliability over prior art switches by avoiding physical contact in switch actuator areas.

It is yet another object of the present invention to provide a MEMS switch structure which has better fatigue properties and better long term stability than prior art switches, is not sensitive to surface charging and stiction in electrostatic actuator areas, and, with simple modifications, can be used as a tunable capacitor.

It is yet a further object of the present invention to provide a fabrication process that allows fabrication of the MEMS switch structure directly on substrates containing pre- processed circuits, such as monolithic microwave integrated circuits (MMIC), and on pre-processed ceramic substrates, such as low temperature co-fired ceramic (LTCC).

The switch of the present invention includes a cantilever, made from a dielectric material, that is suspended at central points of attachment on a substrate. The cantilever contains two or more conducting electrodes, positioned on either side of the points of attachment. When an electric potential is applied between either electrode and a fixed counter electrode on the substrate, an electrostatic force is generated and exerted on the cantilever, causing it to deflect and eventually make mechanical contact at one of its tips with the substrate. A conductive layer on the cantilever tips provides electrical contact between two electrodes on the substrate when mechanical contact is made. When the electrical potential is removed and applied to an electrode on the opposite side of the points of attachment, the contacting tip of the cantilever will lift off the substrate and the tip at the other end of the cantilever will make mechanical contact, thereby opening one switch and closing another. The switching time of the structure is not governed by the mechanical restoring force of the cantilever, but rather by the electrostatic force generated by the electric potential and the mass of inertia of the cantilever.

The switch structure of the present invention includes means for the fabrication of various electrode structures for RF devices, realizing a potential transmission bandwidth from DC to more than 30GHz. The switch structure is made by micro machining of thin film layers on a substrate. The highest fabrication process temperature is 300 C, which makes the process compatible with pre-processed integrated circuits on the substrate. The processing temperature also makes the fabrication process possible on pre-processed low-temperature co-fired ceramic (LTCC) substrates, allowing the switches to be monolithically integrated with other RF components and circuits.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side cross-sectional view of a prior art MEMS switch in which the mechanical restoring force drives one transition in the switch.

FIG. 2 is a side cross-sectional view of a prior art MEMS switch according in which both state transitions are driven by external forces.

FIG. 3 is a side cross-sectional view of a prior art MEMS switch in which both state transitions are driven by external forces, and in which only a small part of the movable structure carries the RF transmission signal.

FIG. 4 is a partial perspective view of a MEMS switch according to the present invention.

FIG. 5 is a top plan view of the MEMS switch of the present invention.

FIG. 6 is a side cross-sectional view of the MEMS switch of the present invention taken along the section line 6-6 in FIG. 5.

FIG. 7a through 7g are side cross-sectional views of a MEMS switch according to the present invention taken along the section line 6-6 in FIG. 5 at different stages of the fabrication process.

FIG. 8 is a top plan view of a MEMS tunable capacitor according to the present invention.

FIG. 9 is a side cross-sectional view of the MEMS tunable capacitor of the present invention taken along the section line 9-9 in FIG. 8.

FIG. 10 is a top plan view of another MEMS tunable capacitor according to the present invention.

FIG. 11 is a side cross-sectional view of the MEMS tunable capacitor of the present invention taken along the section line 11-11 in FIG. 10.

FIG. 12 is a perspective view of a hybrid integration of a bank of MEMS switches of the present invention with an external control circuit.

FIG.13 is a perspective view of MEMS switches of the present invention integrated monolithically with control circuits.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Figures 4 to 6 show various views of a preferred microelectromechanical switch 100 according to the present invention. Switch 100 includes a cantilever 116 that is suspended at two points of attachment 117A and 117B, through torsional beams 124A and 124B, enabling cantilever 116 to tilt around an axis 122. Cantilever 116 is made from an electrically insulating material, such as silicon dioxide or silicon nitride. On the underside of suspended cantilever 116 are two conducting electrodes 114 and 118, and two conducting contact strips 113A and 113B. Several holes 121 are made in cantilever 116 around electrodes 114 and 118 to allow air to escape from the gap under cantilever 116 during operation. Contact strips 113A and 113B are used to create electrical contact between center conductors 111A and 111B, which with strips 112A and 112B form transmission lines 125A and 125B, respectively, at either end of cantilever 116. Transmission lines 125A and 125B are co-planar transmission lines in which strips 112A and 112B are finite-extending ground planes and conductor strips 111A and 111B are signal planes. It will be apparent to those skilled in the art, that the configuration of transmission lines 125A and 125B can be readily changed to a microstrip, stripline, or

other similar configuration. For example, in a microstrip configuration, groundstrips 112A and 112B are replaced with a ground plane on the bottom side of substrate 120. In a stripline configuration, another ground plane, typically as a part of package, is added above the microstrip configuration. Note that signal lines 111A and 111B remain the same, though the their widths might change. The only difference between these configurations is the number of ground planes and their location with respect to a signal line. Transmission lines 125A and 125B are formed in conjunction with actuator counter electrodes 115 and 119, respectively, in a single low resistivity metal, such as copper or silver. Conductors 113A, 113B, 114 and 118 on cantilever 116 are preferably made from a low contact resistance metal, such as gold. Transmission lines 123A and 123B are also covered with a low contact resistance material, such as gold, in contact areas where conductors 111A and 111B overlap contact strips 113A and 113B, respectively. In operation, an electrical potential is applied across either electrode set 114 and 115, or 118 and 119, whereby an electrostatic attraction force is generated between the electrodes which causes cantilever 116 to tilt around axis 122. Since the electrostatic force is inversely proportional to the electrode separation, any displacement due to attraction serves to increase the electrostatic force. In addition, since the mechanical restoring force of the suspension at points 117A and 117B is designed to be much smaller, this is an inherently unstable condition. As a result, cantilever 116 will tilt until one of its tips makes physical contact in the areas where the conductors 111A and 111B and strips 113A and 113B overlap. The locations of actuator electrode sets 114 and 115 and 118 and 119 are chosen, such that when one of cantilever 116's tips makes contact, an air gap remains between actuator electrodes 114 and 115 or 118 and 119, depending on the

particular tip making contact. This prevents short-circuiting and also eliminates the need for an insulator in the actuators, which eliminates problems with surface charging and stiction. Thus, for example, if cantilever 116 is making contact with transmission line 125A, to toggle switch 100, the electrical potential is removed from actuator electrodes 114 and 115 and applied to the opposing electrode set 118 and 119, which will cause cantilever 116 to tilt in the opposite direction until mechanical contact is made by cantilever 116 at the opposing transmission line 125B.

The switches constructed as shown in FIG. 4 can be used as tunable capacitors if the electrostatic voltage applied between the actuation electrodes is kept below the actuation voltage of switch 100. Considerable change in capacitance is obtained with this mode of operation of the switches. Such tunable capacitors can be used in various ways to modify the wave propagation in high frequency circuits.

One preferred embodiment of a MEMS tunable capacitor configuration 200 is shown in Figures 8 and 9. Similar to switch 100, capacitor 200 includes a cantilever 201 supported at its midpoint. Suspended cantilever 201 has conducting strips 213 and 214 for actuation and a plate 207 that is the upper plate of the parallel-plate capacitor. The lower plate 206 of the capacitor is formed directly underneath upper plate 207. Electrical contact between the upper plate 207 and circuits in the lower level is achieved by connection through a contact area 205 of a conducting strip 204. The conducting strips 204 and 206 connect the capacitor 200 to the other circuits (not shown) on the substrate. To make the electrical connection with upper plate 207 at 205, a potential difference larger than the actuation voltage must be applied to actuation pair 213 and 218. Once electrical contact is established between plates 207 and strip 204, the capacitance

between the plates 207 and 206 is changed by increasing the voltage between actuation pair 213 and 218 beyond the actuation voltage. This reduces the gap between the plates 207 and 206 so that the capacitance increases. To break the contact, the voltage on the other actuation pair 214 and 216 must be applied, while the voltage on the pair 213 and 218 is removed. The conductive island 203 is used as a mechanical stop, so that the physical contact between the actuation pairs 214 and 216 is avoided.

Another preferred embodiment of MEMS tunable capacitor configuration 300 is shown in Figures 10 and 11. This capacitor includes two conducting strips, 313 and 314, for actuation purposes and a strip 307 which serves as the upper plate of capacitor 300, patterned underneath a nonconducting cantilever 301. Each of strips 313 and 314 has a corresponding fixed conducting strip 318 and 316, respectively, patterned on substrate 120. Also formed on substrate 120 is a lower capacitor plate 306. An electrical connection to movable upper plate 307 of capacitor 300 is provided through narrow bridges 319, which connect cantilever 301 to attachment points 317 through which cantilever 301 is attached to substrate 120. The width of bridges 319 may be constrained due to mechanical requirements. This, in turn, can result in a high impedance connection through the bridge that may limit the frequency range of operation of capacitor 300. In this embodiment, both conductive islands 303 and 304 are used as mechanical stops.

A preferred process for fabricating the switch and capacitors of the present invention is based on semiconductor thin film deposition and photolithography processes, which are well known in the prior art. The preferred fabrication process is illustrated in Figures 7a-7g, with each figure being a cross-sectional view taken along the section line 6-6 in Figure 5 at different stages of the fabrication process.

As shown in Figure 7a, first a layer of low resistivity metal 131, such as copper or silver, is deposited on substrate 120. Substrate 120 may or may not contain preprocessed circuits, components, or interconnections. A thin layer of low contact resistance metal 132, such as gold, is then deposited on layer 131 and patterned, using photolithography, to form contact areas 123A and 123B in switch 100. A masking layer of chemically resistant material 133, such as chromium, silicon dioxide or polyimide, is then deposited and patterned using photolithography. Masking layer 133 is used later in the process to form electrical transmission lines 125A and 125B and fixed counter electrodes 115 and 119 on substrate 120. As shown in Figure 7b, a sacrificial layer 134, such as aluminum, is then deposited, and openings are made in layer 134 using photolithography, which then serves as points of attachment 117A and 117B for cantilever 116. Referring now to Figure 7c, a thin layer of low contact resistance metal 135, such as gold, is then deposited and patterned using photolithography to form actuator electrodes 114 and 118 and contact strips 113A and 113B on switch cantilever 116. As shown in Figure 7d, a layer of dielectric material 136, such as silicon nitride, is then deposited and patterned using photolithography to form switch 100's cantilever 116. Sacrificial layer 134 (Figure 7b), is then removed, as shown in Figure 7e, to release cantilever 116 and expose layers 131 and 133. As shown in Figure 7f, layer 131 is then patterned using masking layer 133 as a mask to form transmission lines 125A and 125B and actuator counter electrodes 115 and 119 on substrate 120. Finally, in Figure 7g, masking layer 133 is removed to form the complete switch structure 100. In Figure 7g, the reference numerals identifying the components of switch 100 are shown in parentheses along side the reference numerals for the process.

The MEMS switch of the present invention can be used in applications using a low-speed (*i.e.*, switching speed > 1microsecond) and very-low loss electrical switch. High-frequency applications where PIN diodes, FET-based switches, and other mechanical switches are used, can also employ the MEMS switch of the present invention. In particular, several parts of wireless applications can benefit from employing the MEMS switch of the present invention. For example, multiple antennas can be switched in and out of transceiver circuits by using a switching network based on the MEMS switch of the present invention. RF filters can be made reconfigurable by using switches like that of the present invention to include a particular set of inductors, capacitors or transmission lines. The impedance matching between high-frequency components can be improved by employing the MEMS switch and variable capacitors of the present invention. The functionality and efficiency of amplifiers and the quality of oscillators can be improved if the MEMS switches and variable capacitors of the present invention are used to tune them to optimize their operation for a desired criteria.

Figure 12 is a perspective view of a hybrid integration of a bank of MEMS switches of the present invention with an external control circuit. In the configuration of Figure 12, the MEMS switches 412, a configurable circuit 410, and control circuits 416 are integrated on substrate 120. If MEMS switches 412, configurable circuit 410 and control circuits 416 are used in a high-frequency application, substrate 120 would be a low-loss microwave substrate, and each of switches 412 would be fabricated directly on substrate 120, as described above with respect to Figures 7a to 7g. Control circuits 416 would be fabricated using a different process sequence, such as high-voltage bipolar, CMOS, BiCMOS, DMOS (double-diffused MOS) or BiCDMOS (bipolar,CMOS,

DMOS) or similar processes. MEMS switches 412 are controlled by control circuits 416 through connections 414 running between MEMS switches 412 and control circuits 416. The method of integration shown in Figure 12 is preferred if control circuits 416 cannot be formed directly on substrate 120.

Figure 13 is a perspective view of MEMS switches 420 of the present invention integrated monolithically with control circuits. In this alternative method of integration, control circuits 426 are directly fabricated on substrate 120 along with configurable circuits 422 and MEMS switches 420. MEMS switches 420 are controlled via electrical connections 424. In both Figures 12 and 13, the control circuits 416 and 426 can monitor signals inside configurable circuits 410 and 422, respectively, and control the MEMS switches and/or MEMS tunable capacitors accordingly to fine-tune the operation of configurable circuits. This allows the overall system to compensate against the internal or external variations more quickly.

Although the present invention has been described in terms of several preferred embodiments and a preferred process of fabrication, it is not intended that the invention be limited to those embodiments or process. Modifications of the embodiments and process within the spirit of the invention will be apparent to those skilled in the art. The scope of the invention is defined by the claims that follow.

What is claimed is:

1. A switch formed on a substrate comprising:

a tilting cantilever arm attached to the substrate;

at least one first electrode formed near each tip of the cantilever arm;

at least two second electrodes formed on the cantilever arm, the second electrodes being formed on opposite sides of where the cantilever arm is attached to the substrate;

at least two third electrodes formed on the substrate, each third electrode being located substantially under a corresponding second electrode; and

at least two fourth electrodes formed on the substrate, each fourth electrode being located substantially under a corresponding first electrode;

whereby each pair of corresponding second and third electrodes forms an air gap capacitor, which when electrically charged provides an electrostatic attraction force, which when exerted on the cantilever arm causes it to tilt so that mechanical contact is made between a correspond pair of first electrodes and fourth electrodes.

2. The switch according to claim 1, wherein the electrostatic attraction force provided by each pair of electrically charged corresponding second and third electrodes is sufficient to deflect the cantilever arm far enough to drive the switch into an ON or OFF state.

3. The switch according to claim 1, wherein the cantilever contains at least one hole near each air gap capacitor to allow air within the gap to escape, thereby reducing squeeze film damping and increasing the switch's mechanical bandwidth.

4. The switch according to claim 1, wherein the cantilever arm is attached to the substrate through several points of attachment that are centrally located on the cantilever arm.

5. The switch according to claim 1, wherein the at least one first electrode and the at least two second electrodes are formed on the cantilever arm's underside.

6. The switch according to claim 1, wherein the at least two fourth electrodes are electrical transmission lines formed on the substrate.

7. The switch according to claim 1, wherein the substrate is a semiconductor material or a material selected from the group consisting of quartz, fused silica, polymer and ceramic.

8. The switch according to claim 1, wherein the substrate includes integrated electronic circuits made prior to fabrication of the switch.

9. The switch according claim7, wherein the ceramic is a material selected from the group consisting of a low-temperature co-fired ceramic (LTCC) and high temperature co-fired ceramic (HTCC).

10. The switch according to claim 1, wherein said cantilever is made from a material selected from the group consisting of silicon, germanium, silicon dioxide, silicon nitride, silicon oxynitride, and polyimide.

11. The switch according to claim 1, wherein the first, second and third electrodes are each made from one or more materials selected from the group consisting of copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, platinum, palladium, titanium, and tungsten.

12. The switch according to claim 1, wherein the substrate also contains at least one integrated electronic circuit fabricated with the switch on the substrate.

13. The switch according to claim 12, wherein the at least one integrated electronic circuit is a control circuit.

14. The switch according to claim 13, wherein the substrate includes a plurality of integrated electronic circuits that include at least one control circuit and at least one configurable circuit.

15. The electromechanical switch according claim 1, wherein the substrate is either a low-temperature co-fired ceramic (LTCC) or a high temperature co-fired ceramic (HTCC).

16. The switch according to claim 6, wherein the transmission lines are co-planar transmission lines.

17. The switch according to claim 6, wherein the transmission lines are microstrip transmission lines.

18. The switch according to claim 6, wherein the transmission lines are strip transmission lines.

19. An electromechanical switch comprising:

a substrate containing an electrically non-conductive surface;

a first electrically conducting layer partially covering said substrate;

means for forming patterns in said first electrically conducting layer using a separate masking layer, allowing formation of said patterns after the completion of overlying structures in said switch;

a cantilever made from a non-conductive material attached to said substrate at two or more points of attachment, creating a tilting axis for said cantilever;

means to form an air gap between said cantilever and said substrate;

a second electrically conducting layer partially covering the underside of said cantilever, arranged with respect to said first conducting layer and said points of attachment, such that said cantilever will tilt around said tilting axis, due to electrostatic attraction, when an electrical potential difference is applied between said first and second conducting layers;

one or more electrically conducting islands in said second electrically conducting layer, which when said cantilever tilts approaches, or makes mechanical contact to, one or more areas of said first electrically conducting layer;

means for electrical connection of said conducting layers to external control circuits or control circuits already contained in the substrate;

means for allowing air in said air gap to escape during tilting of said cantilever.

20. The electromechanical switch according to claim 19, wherein said substrate is a semiconductor material or a material selected from the group consisting of quartz, fused silica, polymer and ceramic.

21. The electromechanical switch according to claim 20, wherein said semiconductor substrate contains integrated electronic circuits made prior to fabrication of said electromechanical switch.

22. The electromechanical switch according claim 20, wherein said ceramic is a low-temperature co-fired ceramic (LTCC) or high temperature co-fired ceramic (HTCC).

23. The electromechanical switch according to claim 22, wherein electrical transmission lines are fabricated in said LTCC or HTCC prior to the fabrication of said electromechanical switch.

24. The electromechanical switch according to claim 19, wherein said first and second electrically conducting layers and the electrically isolated island are each made from one or more materials selected from the group consisting of copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, platinum, palladium, titanium, and tungsten.

25. The electromechanical switch according to claim 19, wherein said masking layer is made from one or more materials from the group consisting of chromium, copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, palladium, platinum, titanium, tungsten, silicon, silicon dioxide, silicon nitride, silicon oxynitride, photoresist, and polyimide.

26. The electromechanical switch according to claim 19, wherein said cantilever is made from a material selected from the group consisting of silicon, germanium, silicon dioxide, silicon nitride, silicon oxynitride, and polyimide.

27. The electromechanical switch according to claim 19, wherein said air gap is formed by deposition and subsequent removal of a sacrificial layer.

28. The electromechanical switch according to claim 27, wherein said sacrificial layer is made from one or more materials from the group consisting of copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, palladium, platinum, titanium, tungsten, silicon, silicon oxide, silicon nitride, silicon oxynitride, photoresist, or polyimide.

29. The electromechanical switch according to claim 19, wherein said means for allowing air to escape from said air gap during tilting of said cantilever is a plurality of holes made through the interior of said cantilever.

30. The electromechanical switch according to claim 19, wherein a third electrically conductive contact layer is placed on said first electrically conductive layer in areas where said first conductive layer overlaps said electrically isolated islands in said second electrically conductive layer.

31. The electromechanical switch according to claim 19, wherein said third electrically conductive layer is made from gold, silver, palladium, platinum, copper, aluminum, or alloys thereof.

32. The electromechanical switch according to claim 19, wherein at least two separate overlapping areas are made in said first and second electrically conducting layers.

33. The electromechanical switch according to claim 32, wherein said overlapping areas form at least two electrostatic air gap actuators.

34. The electromechanical switch according to claim 33, wherein said electrostatic air gap actuators are supplied with at least two separate electrical control potentials.

35. The electromechanical switch according to claim 34, wherein said electrical control potentials are DC voltages or voltages that vary with time.

36. The electromechanical switch according to claim 34, wherein said electrical control potentials are chosen such that when applied to said electrostatic air gap actuators the tip of said cantilever makes mechanical contact with said first conductive layer.

37. The electromechanical switch from claim 34, wherein said electrical potentials are chosen such that a controlled displacement of said cantilever with or without mechanical contact at the tip of said cantilever is realized.

38. The electromechanical switch according to claim 37, wherein said switch is a tunable capacitor.

39. The electromechanical switch according to claim 19, wherein one or more RF transmission lines are formed in said first electrically conducting layer.

40. The electromechanical switch according to claim 39, wherein said switch is an RF electromechanical switch.

41. The electromechanical switch according to claim 39, wherein said switch is an RF tunable capacitor.

42. A tunable capacitor formed on a substrate comprising:

a tilting cantilever arm attached to the substrate;

at least one upper plate of the capacitor formed on the cantilever arm;

at least two first electrodes formed on the cantilever arm, the first electrodes being formed on opposite sides of where the cantilever arm is attached to the substrate;

at least two second electrodes formed on the substrate, each second electrode being located substantially under a corresponding first electrode; and

at least one lower plate of the capacitor formed on the substrate, the lower plate being located substantially under the upper plate;

whereby each pair of corresponding first and second electrodes forms an air gap capacitor, which when electrically charged provides an electrostatic attraction force,

which when exerted on the cantilever arm causes it to tilt so as to change a gap between the upper and lower plates.

43. The capacitor according to claim 42 further comprising a conducting strip formed on the substrate and a contact area formed on the conducting strip for making electrical contact with the upper plate.

44. The capacitor according to claim 42, wherein the electrostatic attraction force provided by each pair of electrically charged corresponding first and second electrodes is insufficient to deflect the cantilever arm far enough to cause mechanical contact between the upper and lower plates.

45. The capacitor according to claim 42, wherein the cantilever contains at least one hole near each air gap capacitor to allow air within the gap to escape, thereby reducing squeeze film damping.

46. The capacitor according to claim 42, wherein the substrate also contains at least one integrated circuit fabricated with the capacitor on the substrate.

47. The capacitor according to claim 42, wherein the substrate is either a low temperature co-fired ceramic or a high temperature co-fired ceramic.

48. A method of fabricating an electromechanical switch or a tunable capacitor comprising the steps of:

depositing a layer of low resistivity metal on a substrate;

depositing a thin layer of low contact resistance metal and patterning the low contact resistance metal layer using photolithography to form the contact areas in the switch;

depositing a masking layer of chemically resistant material and patterning the layer of chemically resistant material using photolithography;

depositing a sacrificial layer and patterning the sacrificial layer using photolithography to form openings in the sacrificial layer that serve as points of attachment for a switch cantilever;

depositing a second thin layer of low contact resistance metal and patterning the layer of low contact resistance metal using photolithography to form actuator electrodes and contact strips on the switch cantilever;

depositing a layer of dielectric material and patterning the layer of dielectric material using photolithography to form the switch cantilever;

removing the sacrificial layer to release the cantilever and expose the layer of low resistivity metal and the masking layer of chemically resistant material;

patterning the layer of low resistivity metal using the masking layer of chemically resistant material as a mask to form transmission lines and actuator counter electrodes on the substrate;

removing the masking layer of chemically resistant material to form the switches' complete structure.

49. The method of claim 48 wherein the layer of low resistivity metal is made from one or more materials selected from the group consisting of copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, platinum, palladium, titanium, and tungsten.

50. The method of claim 48 wherein the layers of low contact resistance metal is made from one or more materials selected from the group consisting of copper, gold,

silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, platinum, palladium, titanium, and tungsten.

51. The method of claim 48 wherein the masking layer of chemically resistant material is made from one or more materials from the group consisting of chromium, copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, palladium, platinum, titanium, tungsten, silicon, silicon dioxide, silicon nitride, silicon oxynitride, photoresist, and polymide.

52. The method of claim 48 wherein the sacrificial layer is made from one or more materials from the group consisting of copper, gold, silver, aluminum, beryllium, iridium, magnesium, iron, nickel, tin, palladium, platinum, titanium, tungsten, silicon, silicon oxide, silicon nitride, silicon oxynitride, photoresist, or polymide.

53. The method of claim 48 wherein the layer of dielectric material is selected from the group consisting of silicon, germanium, silicon dioxide, silicon nitride, silicon oxynitride, and polyimide.

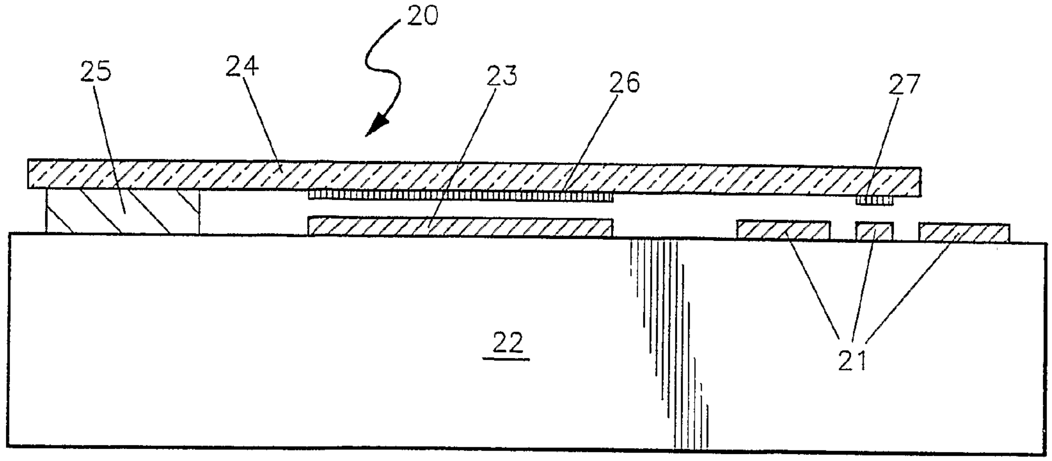

FIG. 1 (Prior Art)

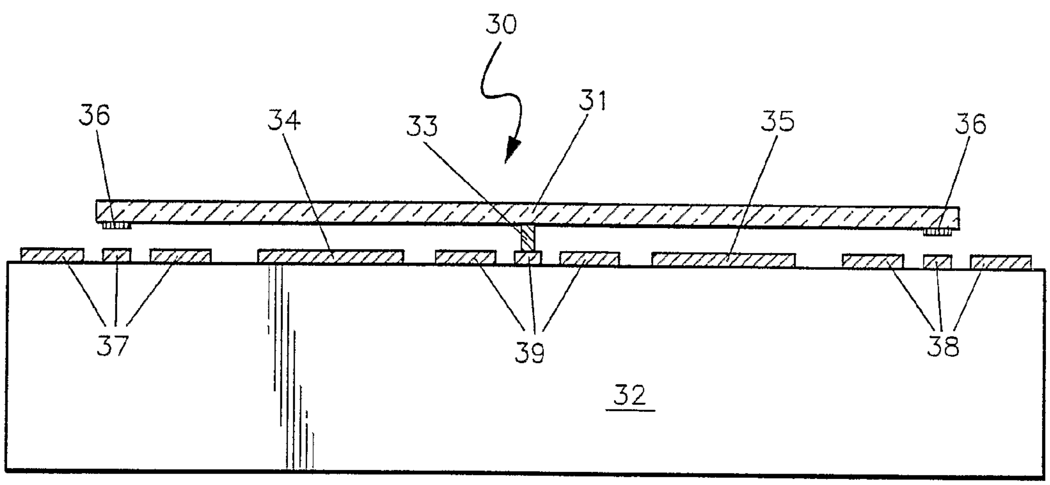

FIG. 2 (Prior Art)

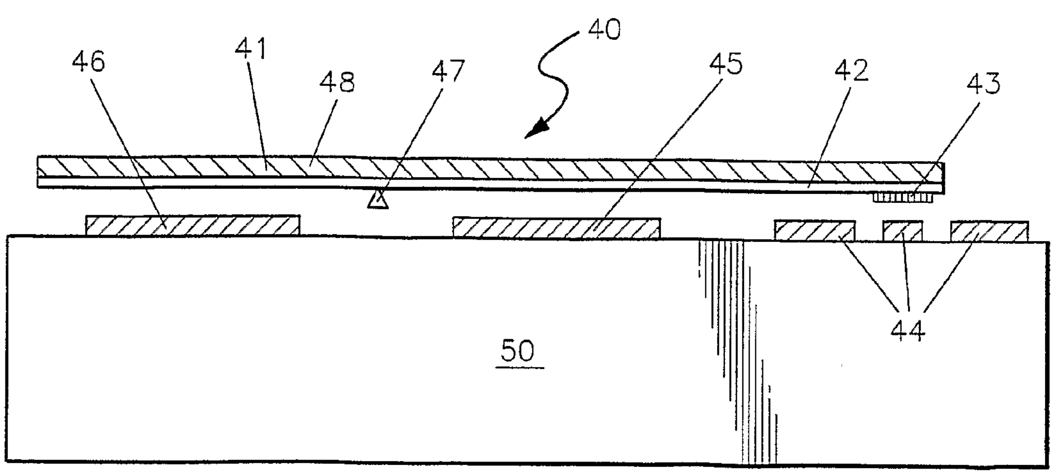

FIG. 3 (Prior Art)

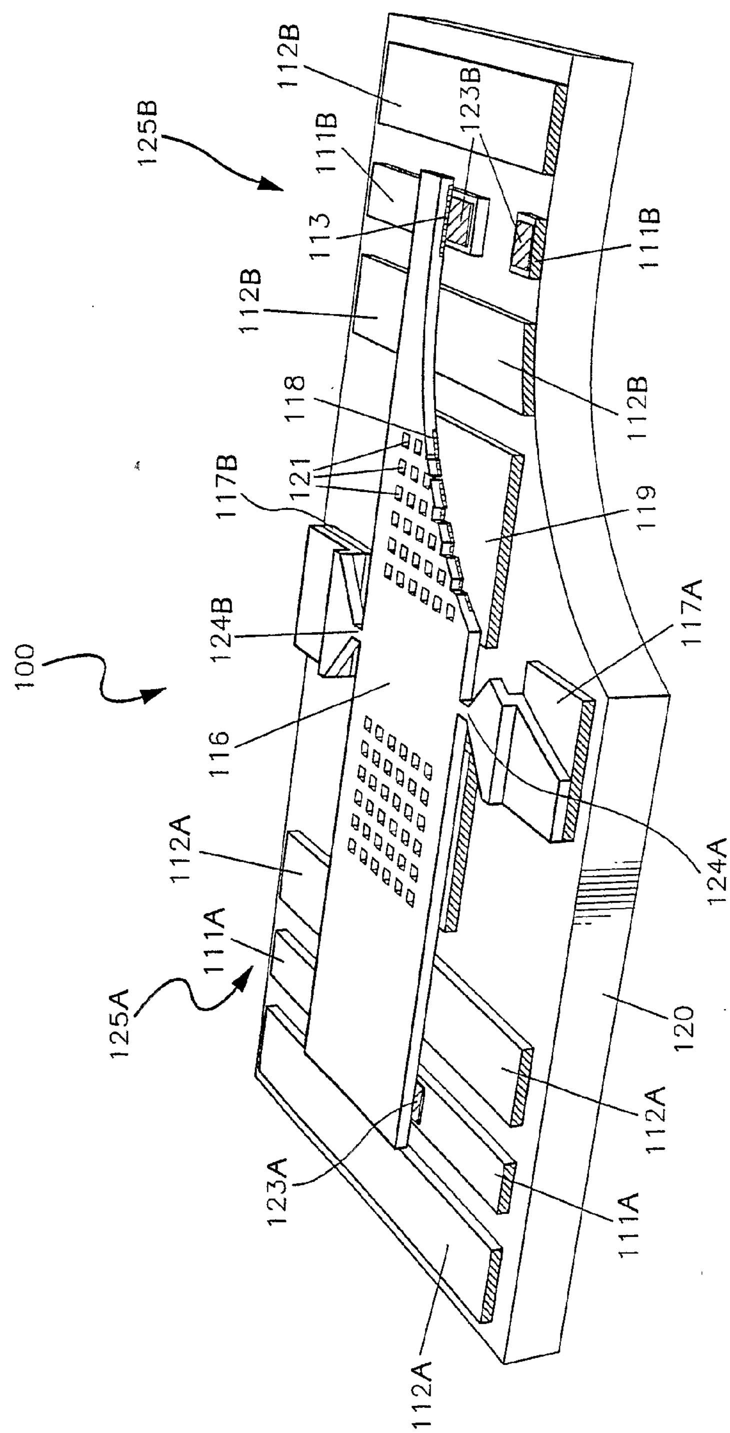

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FIG. 4

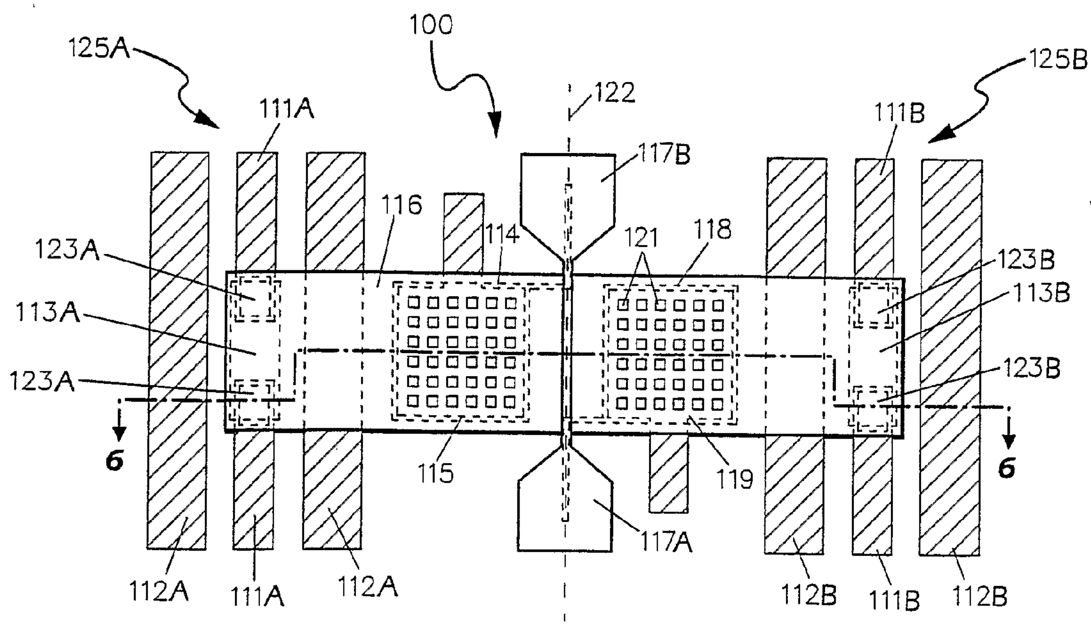
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FIG. 5

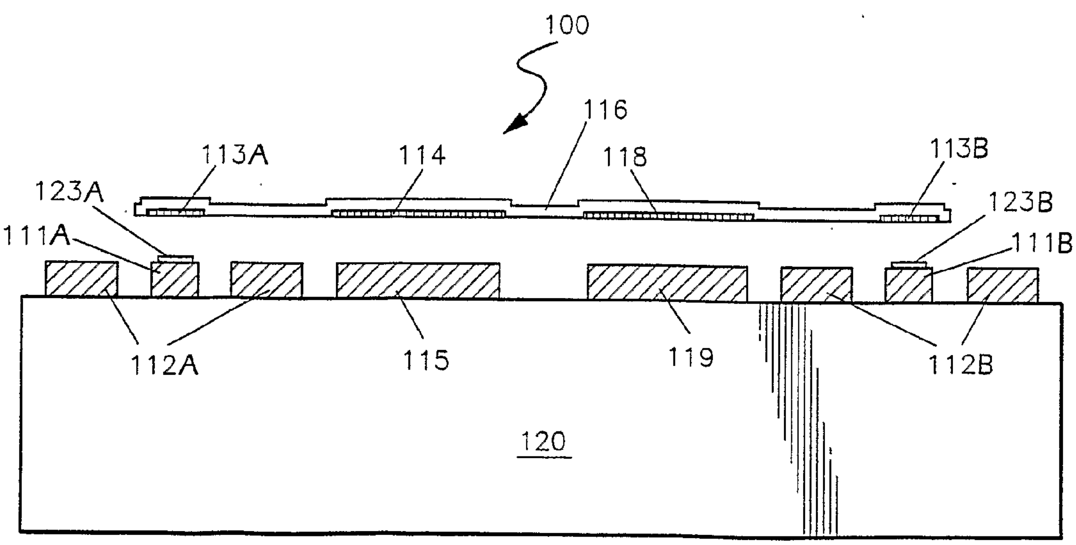
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FIG. 6

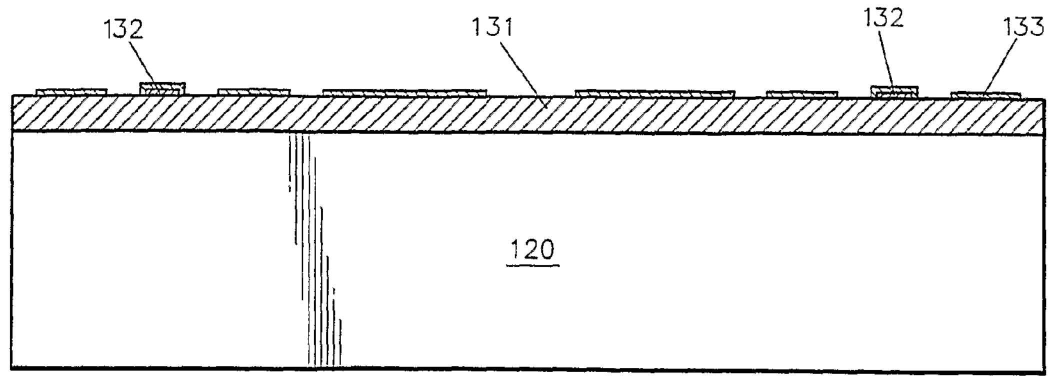

FIG. 7a

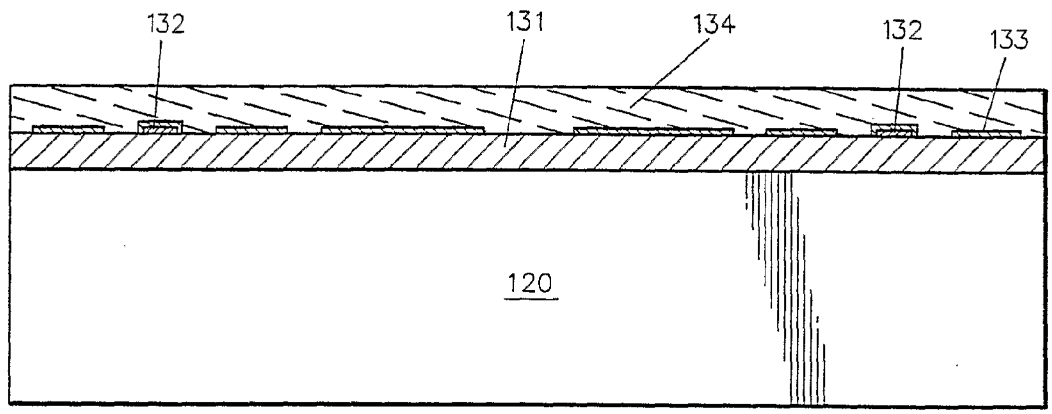

FIG. 7b

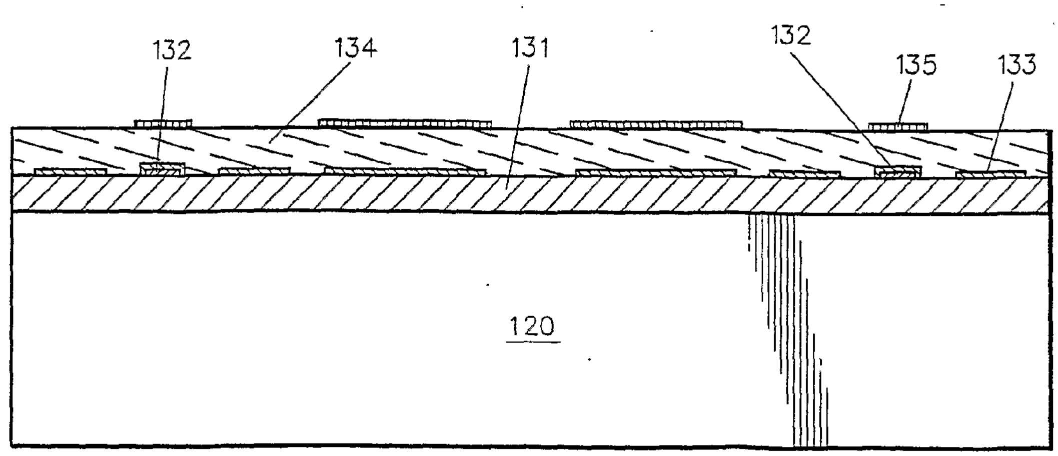

FIG. 7c

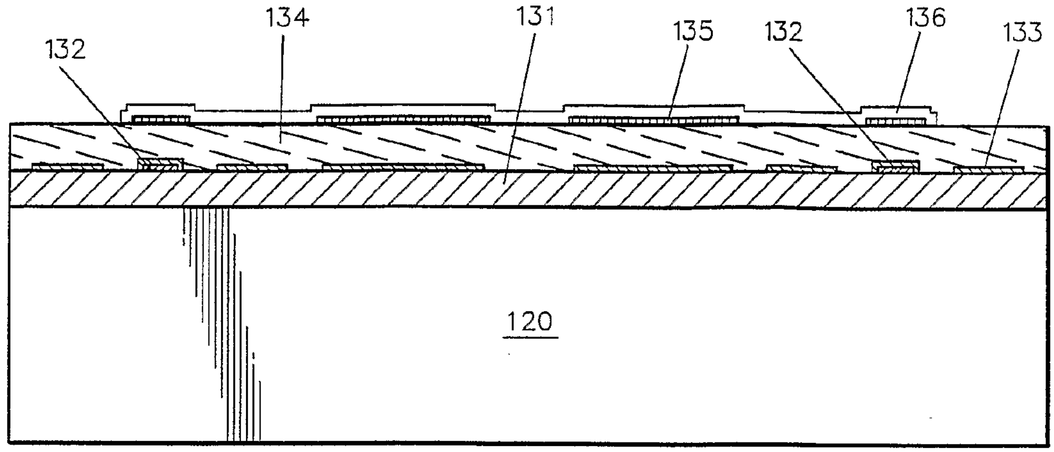

FIG. 7d

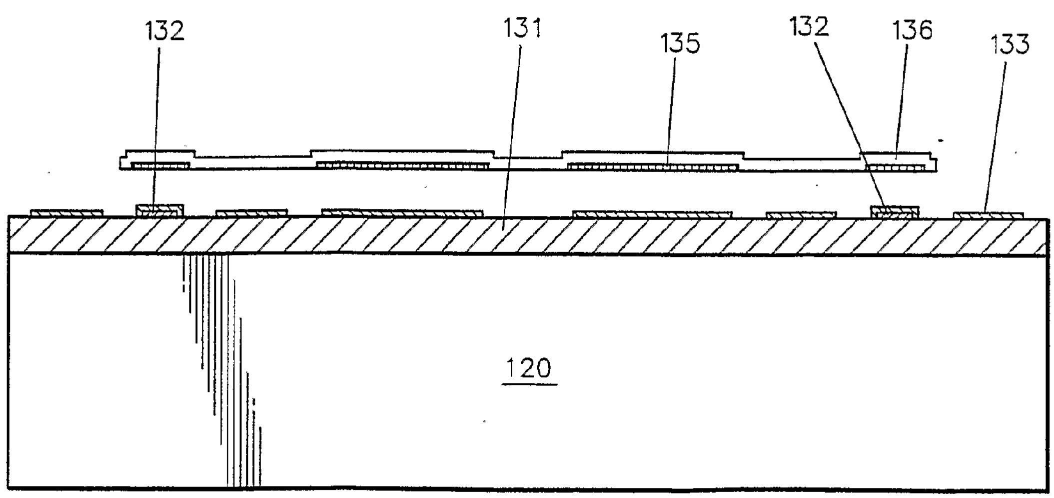

FIG. 7e

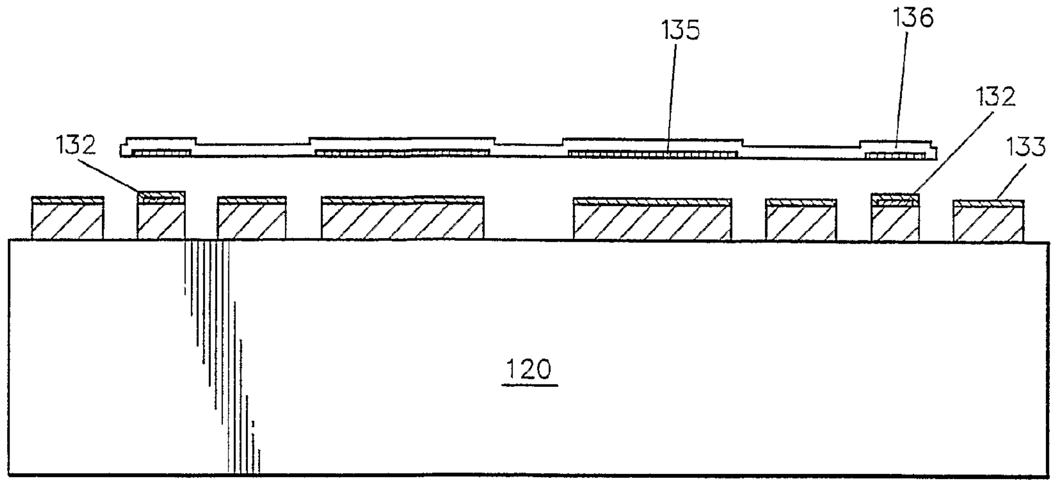
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FIG. 7f

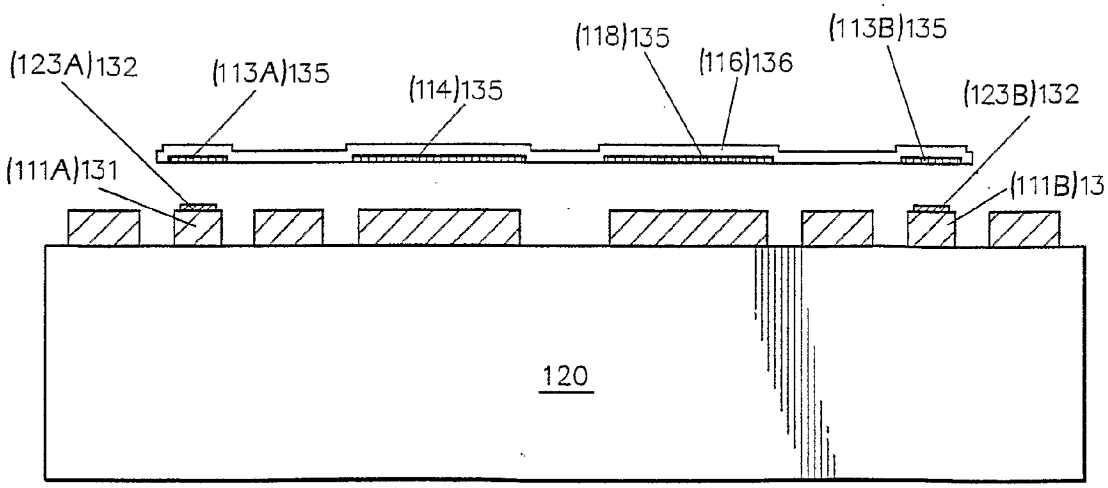
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FIG. 7g

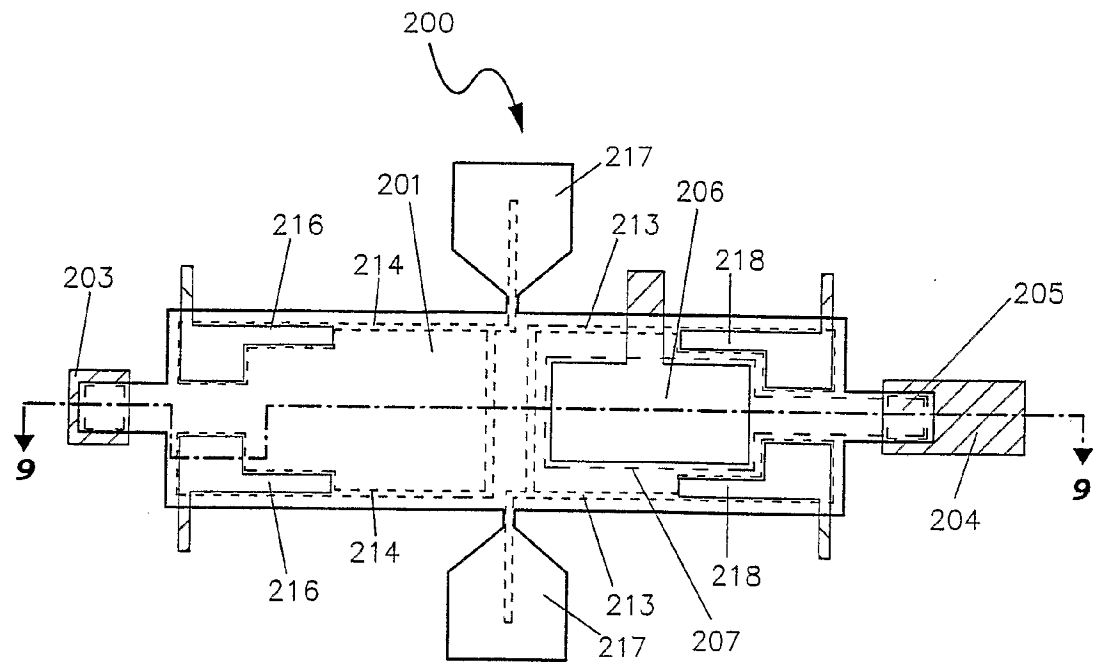
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FIG. 8

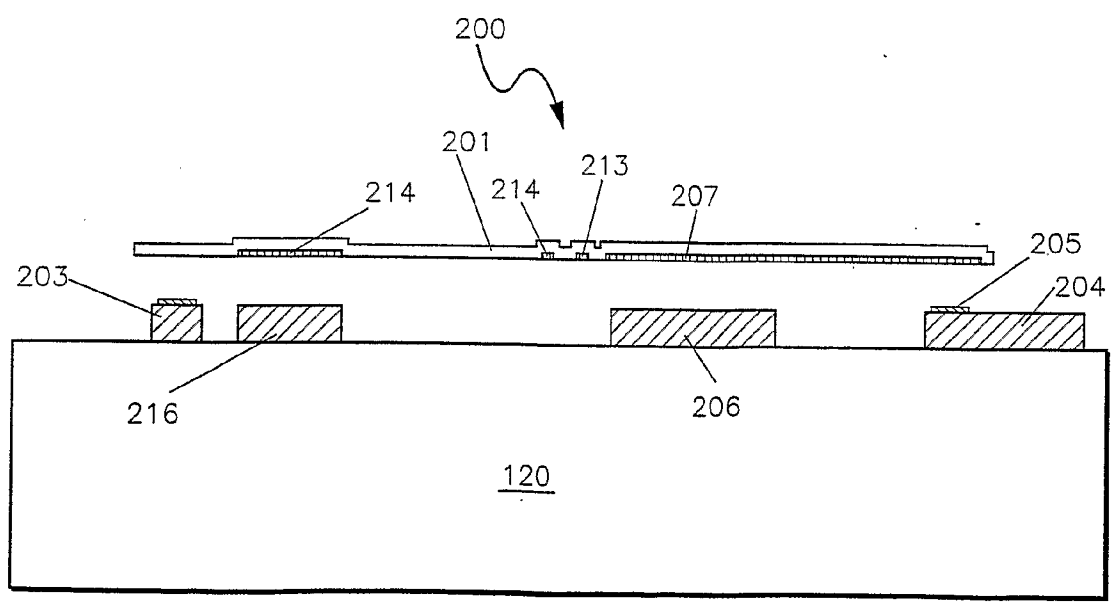
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FIG. 9

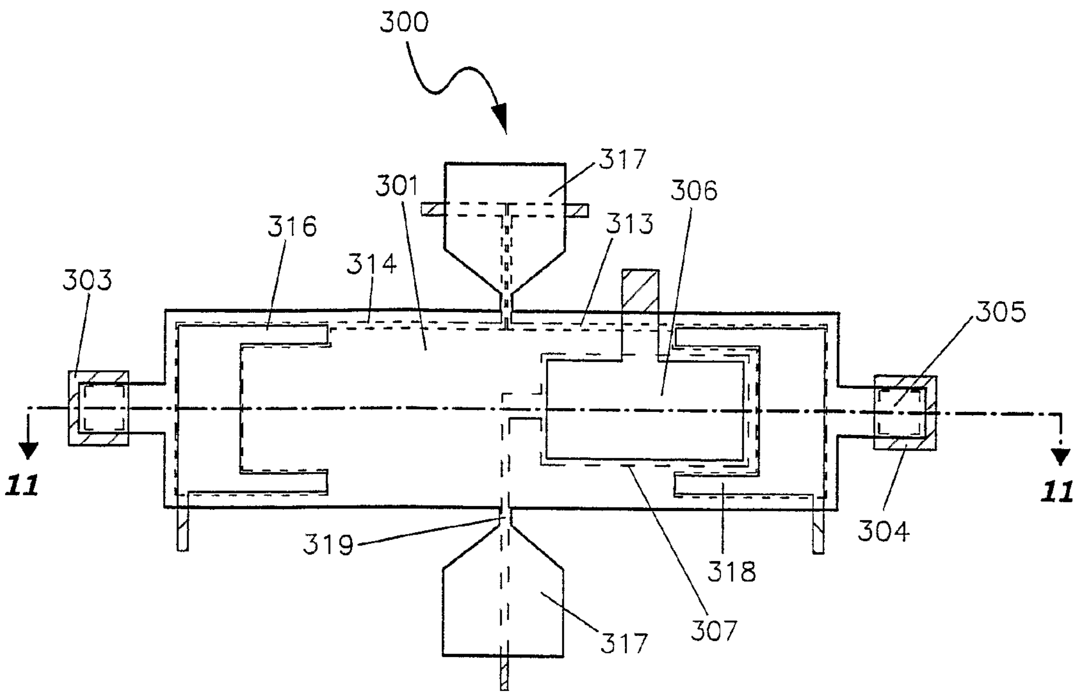
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FIG. 10

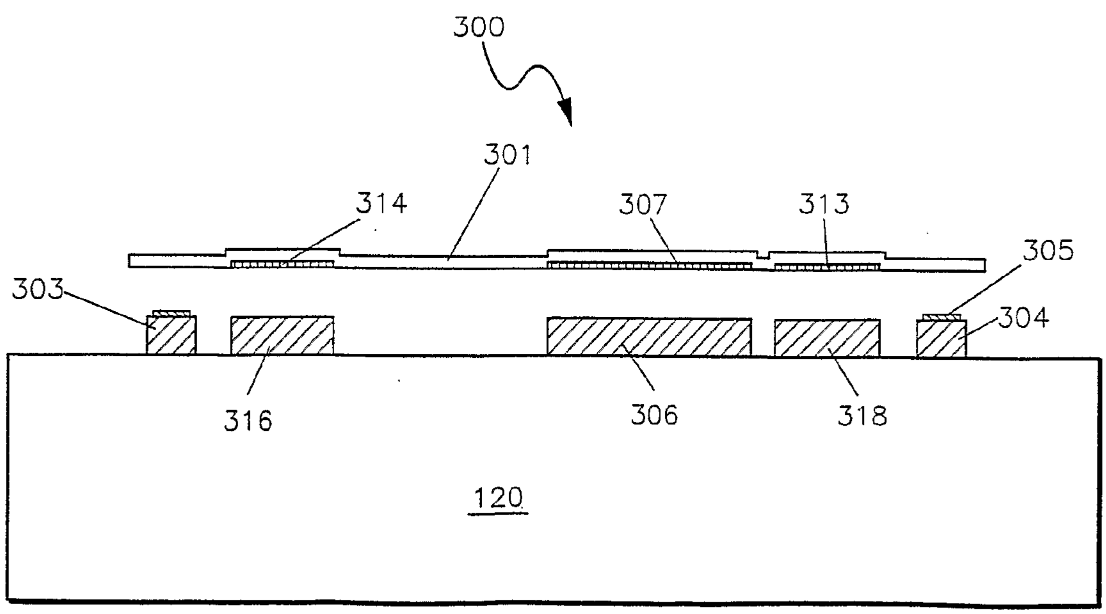
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FIG. 11

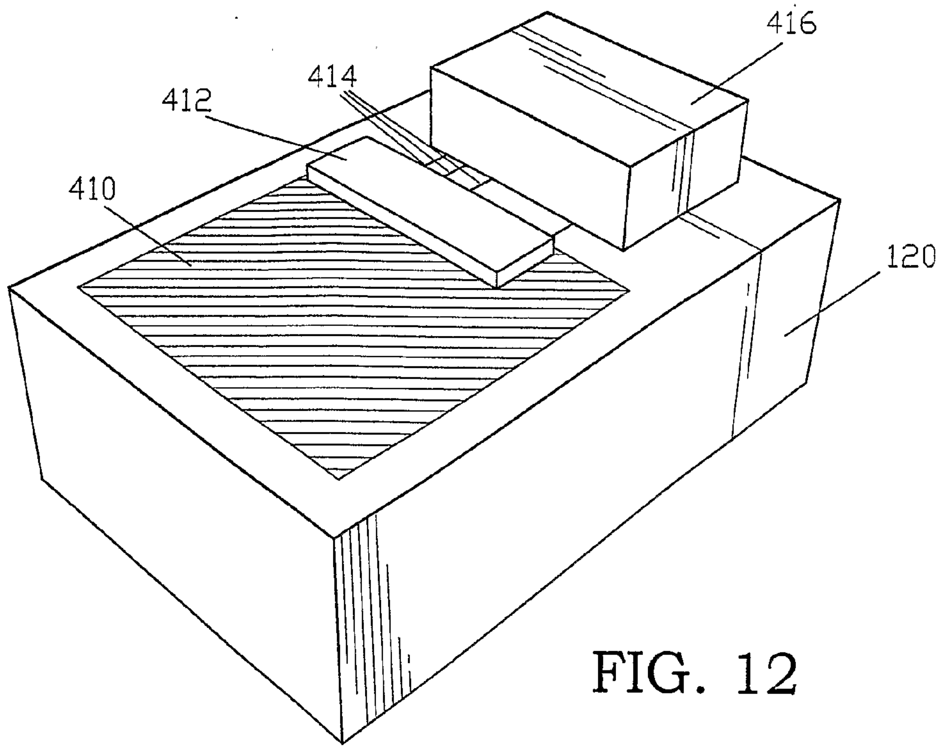

FIG. 12

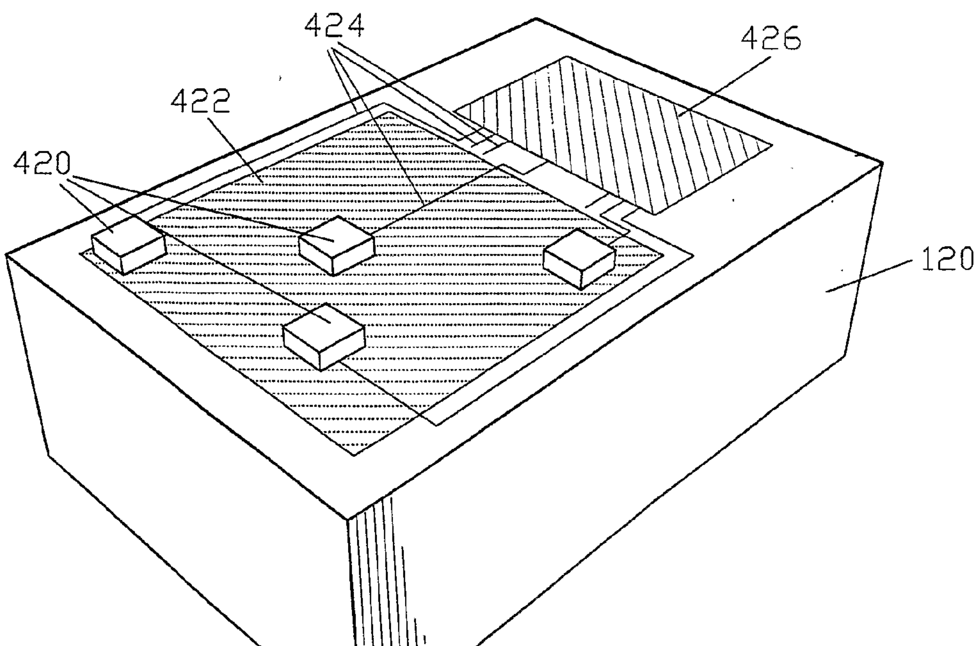

FIG. 13